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Constraints on Dilution From a Narrow Attentional Zoom Reveal How Spatial and Color Cues Direct Selection

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Abstract

Distractor interference is subject to dilution from other nontarget elements, and the level of dilution is affected by attention. This study explores the nature of dilution when the location and color of the target is known in advance. Experiments 1 and 2 show that attention is effectively limited to the precued region, so that it is the non-target letters appearing at the cued locations that are responsible for most of the dilution, and not those appearing at the uncued locations. Furthermore, this dilution occurs relatively early in processing. Experiment 3 demonstrates that top-down attentional control can prevent dilution, because foreknowledge of the target color leads to quick attention shifts. Experiment 4 illustrates bottom-up attentional control in preventing dilution when the distractor is a color singleton that is segregated from the diluting nontargets. The results show that dilution is modulated by both top-down and bottom-up factors, that it can occur even when attention is restricted to a relatively small region, and that it occurs early in processing, but not so early that it avoids the effects of attention. They provide new challenges for earlier accounts suggesting that dilution is widespread and unfettered by attention. Likewise, some parts of the results are difficult to reconcile with the alternative perceptual load theory, but they do support a form of dilution that is limited by attentional boundaries. Because of that link to attention, dilution is a useful tool for measuring how attention is guided by information about target location and color.

Key words: selective attention, distractor interference, perceptual load, dilution, attentional focus

1. Introduction

Among the many experimental tools that have been used to study the allocation of visual attention, one of the most useful has been the interference from a distractor object placed near a visual target. Eriksen and Hoffman (1973) and Eriksen and Eriksen (1974) demonstrated this interference with a simple task that required participants to report a single letter. The response could be speeded or slowed by distractor letters near the target, depending on whether the response associated with the distractors was congruent or incongruent with the correct response to the target. Even though participants knew exactly where the target letter would appear, they were unable to prevent the distractors from being processed and activating responses. This congruency effect demonstrates that the distractors were receiving a certain amount of spatial attention.

Just as a target stimulus is subject to interference from distractors, recent experiments have demonstrated that the interference from a distractor is also subject to interference from other objects in the display. This interference of distractor interference is known as dilution (Kahneman & Chajczyk, 1983; Tsal & Benoni, 2010; Wilson, Muroi, & MacLeod, 2011), because the presence of additional stimuli weakens, or dilutes, the interference from the distractor. Dilution has come to play a theoretically important role in the debate over how attention is affected by perceptual load. Lavie (1995; Lavie & Tsal, 1994) has proposed that visual attention is a resource with a limited capacity, and it will be allocated as necessary to perform perceptual tasks. If attentional capacity remains unused after the demands of a task have been met, then this surplus capacity is automatically allocated to stimuli that are irrelevant to the task. This theory of perceptual load has been supported by experiments demonstrating a decrease in distractor interference as perceptual load increases. (See Lavie, 2005, for a review.)

There have been a number of theoretical challenges to perceptual load theory. For example, the perceptual load effect can be eliminated or reversed when the location of the target is known in advance (Chen & Cave, 2013; Johnson, McGrath, & McNeil, 2002; Paquet & Craig, 1997), when the relevant and irrelevant information are part of the same object (Chen, 2003), when perceptual grouping is used to segregate the target from the distractors (Baylis & Driver, 1992; Cosman & Vecera, 2012; Yeh & Lin, 2013), and when perceptual load is manipulated within a block rather than between different blocks (Murray & Jones, 2002; Theeuwes, Kramer, & Belopolsky, 2004). Experiments that vary the relative salience of the target and the distractor (Biggs & Gibson, 2013; Eltiti, Wallace, & Fox, 2005; Yeshurun & Marciano, 2013), the extent of attentional focus required of the task (Chen & Cave, 2013; Chen & Chan, 2007; Miller, 1991), and the spatial uncertainty associated with the distractor or target (Marciano & Yeshurun, 2011; Wilson et al., 2011) have also found results inconsistent with the prediction of the perceptual load theory. Furthermore, a study by Kyllingsbaek, Sy, and Giesbrecht (2011) using a partial report technique (Sperling, 1960) demonstrates that adding irrelevant letters at known distractor locations lowers the number of target letters being reported, suggesting that a certain proportion of attention is allocated to irrelevant stimuli in the display while the target is being processed instead of after the processing of the target is completed.

A related objection to perceptual load theory focuses on experiments (e.g., Lavie & Cox, 1997; Lavie & Fox, 2000) in which perceptual load is increased by adding additional objects to the stimulus display. These extra objects increase perceptual load because they are relevant to the task, and their inclusion lowers the interference from a critical distractor. Both Wilson et al. (2011) and Tsal and Benoni (2010; Benoni &Tsal, 2010) have proposed dilution as an alternative to perceptual load theory for explaining these results. Their experiments demonstrate that distractor interference can be lowered by adding additional objects that are

NOT relevant to the task. These additional items should not increase perceptual load, but their presence nonetheless seems to dilute the distractor interference. Tsal and Benoni claim that the same dilution is responsible for the results of the earlier perceptual load experiments. Lavie and Torralbo (2010) counter that these results can still be explained within the perceptual load theory, because the additional items added to the stimulus array compete with the distractor for the attentional capacity that is not allocated to the target.

Different forms of dilution have been proposed. Tsal and Benoni (2010) did not make strong claims about the mechanisms underlying dilution, but they suggested a simple and straightforward form of dilution in which every object in a search array could interfere with every other object, regardless of whether they were relevant to the task or whether their locations had been cued. This dilution could be caused by interference among basic perceptual properties at an early preattentive processing stage, and so we will refer to it as preattentive dilution. Wilson et al. (2011) proposed a different mechanism for dilution, which shares some of the same theoretical assumptions as perceptual load theory. Their dilution mechanism operates after attention has selected a single object as the target. The nontarget stimuli compete for any attentional capacity not allocated to the target, causing each to dilute the effects of the others. We will describe this account as post-selection dilution.

Both of these accounts predict that dilution will be widespread across the different objects in the search array, regardless of whether attention is broadly distributed or zoomed in to a small region. Chen and Cave (2013) suggested that the widespread dilution in earlier experiments may have been due to the abrupt onsets of the search array, which could broaden the allocation of attention. In Chen and Cave’s experiments, the stimulus letters were created by removing segments from items that were already visible, as done by Yantis and Jonides (1984). When abrupt onsets were eliminated, the results showed that the level of dilution depended on whether or not the nonrelevant stimuli were within the attended region in the display. Dilution could be eliminated if participants could use foreknowledge about the location of upcoming targets to focus attention narrowly. They also found that attention could effectively block dilution if it was allocated based on the target's color. Additionally, dilution was only produced by letters in their normal upright orientation, and not by inverted letters, indicating that dilution occurs at the level of letter representations, and is not simply interference among simple visual features.

The new experiments presented here will test whether the inter-object interference that produces dilution is widespread across the display, as predicted by preattentive dilution and post-selection dilution, or whether that interference is limited to the region selected by attentional zoom. The earlier experiments by Chen and Cave (2013) tested how attentional zoom limits interference in a simple paradigm in which the locations to be attended were always accurately cued, and uncued locations were completely irrelevant to the task. The new experiments will test dilution under more complex circumstances, with spatial cues that are sometimes invalid. Uncued locations can still be occupied by targets, and are thus still relevant to the task. The results of Experiment 1 show that attention can be effectively constricted to the cued region, so that dilution only arises from stimuli within this region. Experiment 2 shows that this dilution occurs relatively early in the trial. The remaining experiments demonstrate that dilution is also limited by attention that is driven by top-down (Experiment 3) or bottom-up (Experiment 4) color information. These demonstrations of dilution being limited by attentional zoom conflict with the predictions from both preattentive dilution or post-selection dilution, which assume that dilution is more widespread. The results are also difficult to reconcile with perceptual load theory, as explained below, but are consistent with an account based on zoom-limited dilution.

Also, because of the link between dilution and attentional zoom, these experiments provide a new and more precise view of how attention is allocated when spatial expectations are imprecise. In these experiments with spatial cues that are not completely reliable, participants must be prepared for targets that appear outside the cued region, and thus they might be expected to distribute attention more broadly. However, the results show that even with the possibility of invalid cues, spatial attention is still focused mainly at the cued locations, although foreknowledge of the target color can also allow a quick reallocation of attention after the stimulus appears. Dilution is also subject to the effects of color boundaries segregating the stimuli into separate groups. Furthermore, dilution in invalid trials is shown to occur relatively early in visual processing; probably before attention has shifted away from cued locations. With a better understanding of when and how dilution occurs in this paradigm, we also get a clearer picture of the other aspects of attentional allocation, including the joint effect of the spatial and color cues, and the bottom-up effects of color differences in the display.

2. Experiment 1

In the first two experiments by Chen and Cave (2013), either two or six locations could be cued. The target always appeared at a cued location, so that when only two locations were cued, attention could be focused relatively narrowly to exclude many of the stimulus locations. The second of these experiments showed that dilution occurred when attention was broadly distributed in the 6-letter condition, but not when it was more narrowly focused in the 2-letter condition. While this result establishes a link between attentional zoom and dilution, it does not demonstrate specifically how a broad distribution of attention leads to dilution, or whether it is necessary for attention to be broadly distributed in advance, in preparation for a stimulus that has not yet appeared. Experiment 1 addresses this question by testing for dilution with invalid cues, so that the target is outside the cued region.

The initial display on each trial consisted of a number of place-holders, so that there would be no abrupt onset when the target appeared. After that, a precue appeared, and then a target display (see Figure 1). The task was to search for a target letter (H or S) among 2 or 6 irrelevant letters (the 2-letter vs. 6-letter condition). The target, which was equally likely to be congruent or incongruent with a critical distractor, could appear at one of the two cued locations on valid trials or at one of the four uncued locations on invalid trials.

On valid trials, if participants focus their attention on the cued locations, then the attended area should contain only one neutral stimulus regardless of the number of letters in the display. Consequently, zoom-limited dilution predicts that little dilution will occur. In contrast, on invalid trials, participants would have to switch attention to locate the target. As there would be more attended neutral stimuli in the 6-letter condition than in the 2-letter condition both before and after attention is switched from the original cued locations, this would open the door for dilution to occur. As the degree of processing of the critical distractor is inversely related to the number of neutral stimuli receiving attention, the congruency effect should be larger when the target display contains 2 rather than 6 irrelevant letters. Thus, if the valid trials show evidence that attention is narrowly focused, then a dilution effect in the invalid trials will show that dilution can occur even if participants have not prepared for the stimulus by broadly distributing attention in advance.

Furthermore, a comparison of the distractor interference effect between the valid and invalid 6-letter conditions would also allow us to test the zoom-limited dilution account against the perceptual load account. One of the central tenets of the perceptual load theory is that perceptual load is not influenced by task irrelevant stimuli. In the present experiment, we can reasonably assume that participants would initially focus their attention on the stimuli at the cued locations, and if a target then occurred at a cued location, they would not switch attention to process other non-target stimuli. In the invalid condition, however, more letters would need to be processed due to the need to switch attention, and the perceptual load theory would predict less distractor interference in the invalid 6-letter condition compared with the valid 6-letter condition. If a comparable degree of distractor processing was found between the two 6-letter conditions, this pattern of data would indicate that the non-target letters initially outside the attentional zoom in the invalid 6-letter condition did not participate very much in the degree of distractor processing, and this, in turn, would suggest that zoom-limited dilution occurs relatively early during the initial focus of attention.

2.1. Method

2.1.1. Participants.

Twenty-six undergraduate students from the University of Canterbury volunteered to participate in the experiment in exchange for course credit or payment (NZ$10). All reported to have normal or corrected-to-normal vision.

2.1.2. Apparatus and Stimuli.

Stimulus displays were shown on a PC with a 16-inch monitor. The participants were tested individually in a dimly lit room. The viewing distance was approximately 60 cm. E-prime 2.0 (Psychology Software Tools, Pittsburgh, PA) was used to display stimuli and to record responses.

Stimuli were presented against a black background. Each trial consisted of a fixation display, a cue, and a target display. The fixation display consisted of 7 white (RGB = 255, 255, 255) figure-8 stimuli, which also served as place-holders for the stimuli in subsequent displays. Each figure-8 stimulus subtended 0.86^0 of visual angle in height and 0.57^0 in width. One of the stimuli was at fixation, and the rest formed an imaginary circle with a radius of 2.48^0 centered at fixation. The cue display consisted of 4 frames. Frames 2 and 4 were identical to the fixation display. Frames 1 and 3 differed in that two figure-8 stimuli on opposite sides of the circle were gray (RGB = 60, 60, 60). This sequence of four frames was perceived as 2 stimuli dimming twice. The two cued locations were always on opposite sides of the imaginary circle. This same stimulus arrangement was used by Wilson et al. (2011) and by Chen and Cave (2013). Because the two cued locations are equally likely to be the target, participants should have a strong incentive to keep their eyes fixed at the center of the display, between the two cued locations, while waiting for the search array to appear. If participants chose to saccade to a cued location after the cue appeared, the target would appear far away from fixation on half the trials, making the task more difficult on those trials.

The letters in the search array were also white. They were constructed by removing the unneeded segments of the figure-8 stimuli (Yantis & Jonides, 1984). We used offset transients rather than onset transients to create the stimuli in the target display to ensure that the onset of the target display would not differentially affect the initial extent of attentional focus in the 2-letter vs. the 6-letter condition. (See Experiments 1 and 2 in Chen & Cave, 2013, for a detailed description of this logic and empirical evidence supporting the use of offset transients.) The central letter, which was always the critical distractor, was equally likely to be an H or an S. The target was also equally likely to be an H or an S. On half of the trials, the target and distractor were identical (the congruent trials) and on half they were different (the incongruent trials). On 60% of the trials (the valid trials), the target would appear at one of the two cued locations with equal frequency. On the rest of the trials (the invalid trials), the target was equally likely to appear at one of the four uncued locations. The target was always the same distance from the center of the display, so all conditions were matched in their acuity demands. In the 6-letter condition, the search array consisted of the target, the critical distractor and 5 neutral letters (P, E, F, L, and U). In the 2-letter condition, in addition to the target and the critical distractor, the search array consisted of 4 place-holders identical to those in the fixation display and 1 neutral letter selected randomly and with equal probability from the set of five neutral letters mentioned above. Thus, the target was always the same distance from neighboring objects in the 2-letter and 6-letter conditions, so that there would be no difference across conditions in interference from nearby low-level visual features. There were as many 2-letter trials as there were 6-letter ones.

Insert Figure 1 about here

2.1.3. Design and Procedure.

The experiment used a 2 x 2 x 2 within-participants design. The principal manipulations were Validity (valid vs. invalid), DisplaySize (2-letter vs. 6-letter), and Congruency (target and distractor congruent vs. incongruent). All types of trials were presented randomly within a block.

Each trial started with the presentation of a 500 msec fixation display, followed by 2 figure-8 place-holders along the perimeter of the imaginary circle dimming twice, with each dimming lasting 250 msec followed by a 250 msec interval after the 1st dimming and a 500 msec interval after the 2nd dimming. At the end of the 2nd interval (i.e., after the 4th frame of the cue display), the central place-holder would change into an H or an S with equal probability. Depending on the DisplaySize condition, 2 or 6 other place-holders would also change into letters. The target would appear at one of the cued locations on 60% of the trials and at one of the uncued locations on the rest of the trials. The search array stayed on the screen until response. The inter-trial interval was 500 msec.

The participants were provided with the cue validity information. They were instructed to pay attention to the cued locations and to ignore the central distractor. The task was to identify the target as quickly and as accurately as possible. The participants used the index and middle fingers of their right hand to press one of the two designated keys on a response box (the 4th key if the target letter was an "H", and the 5th key if it was an "S"). The entire experiment consisted of 2 blocks of 16 practice trials, followed by 5 blocks of 96 experimental trials with a short break after each block. It took about 35 to 45 minutes to complete the experiment.

2.2. Results and Discussion

In all the experiments reported below, we conducted statistical analyses on both the mean response times and error rates. In no case was there evidence of a speed-accuracy tradeoff. Given that the results of the analyses on the accuracy data were largely consistent with those on RTs, we will report only the RT results unless the results of the analyses on the accuracy data provided additional insight. Mean error rates for each experiment can be found in the table of the relevant experiment.

Figure 2A shows the mean response times. The error rates are shown in Table 1. Two participants' data were excluded because the mean RT of each person was over 3 standard deviations above the average RT of the rest of the participants. A 2 x 2 x 2 repeated-measures analyses of variance (ANOVAs) indicated faster responses on the valid (707 msec) than invalid (846 msec) trials, $F(1, 23) = 75.54$, $MS_e = 12386$, $p < .001$, $\eta_p^2 = .77$, and in the 2-letter (702 msec) than the 6-letter (851 msec) condition, $F(1, 23) = 192.72$, $MS_e = 5532$, $p < .001$, $\eta_p^2 = .89$. Responses were also faster on the congruent (731 msec) rather than incongruent (822 msec) trials, $F(1, 23) = 107.06$, $MS_e = 3760$, $p < .001$, $\eta_p^2 = .82$. There was a significant interaction between DisplaySize and Validity, $F(1, 23) = 20.34$, $MS_e = 4114$, $p < .001$, $\eta_p^2 = .47$, suggesting that response latencies increased more from the 2-letter to 6-letter displays when the cue was invalid (an increase of 191 msec) compared with when it was valid (an increase of 107 msec). DisplaySize also interacted with Congruency, $F(1, 23) = 11.56$, $MS_e = 1220$, $p < .01$, $\eta_p^2 = .33$, indicating a larger congruency effect in the 2-letter condition (108 msec) than in the 6-letter condition (74 msec). Importantly, there was a significant three-way interaction of Validity, DisplaySize, and Congruency, $F(1, 23) = 5.22$, $MS_e = 2098$, $p < .05$, $\eta_p^2 = .18$.

Insert Table 1, Figure 2A and 2B about here

To clarify the three-way interaction, we conducted two separate ANOVAs, one on the valid and the other on the invalid trials. On the valid trials, only the main effects of DisplaySize and Congruency were found, $F(1, 23) = 112.12$, $MS_e = 2463$, $p < .001$, $\eta_p^2 = .83$, and $F(1, 23) = 89.26$, $MS_e = 1908$, $p < .001$, $\eta_p^2 = .80$, for DisplaySize and Congruency, respectively. There was no significant interaction between these two factors, $F(1, 23) < 1$, *ns*. On the invalid trials, all the effects were significant, $F(1, 23) = 121.63$, $MS_e = 7183$, $p < .001$, $\eta_p^2 = .84$, for DisplaySize; $F(1, 23) = 73.30$, $MS_e = 3203$, $p < .001$, $\eta_p^2 = .76$, for Congruency; and $F(1, 23) = 11.46$, $MS_e = 2176$, $p < .01$, $\eta_p^2 = .33$, for their interaction. These results confirmed the absence of a dilution effect on the valid trials, with the magnitude of the congruency effects comparable between the 2-letter condition (86 msec) and the 6-letter condition (83 msec). In contrast, there was a significant dilution effect on the invalid trials. The congruency effect was larger in the 2-letter condition (132 msec) than in the 6-letter condition (67 msec).

The results of Experiment 1 show that dilution can occur even when participants prepare for a trial by focusing attention to a small cued region. On the valid trials, the target appeared at a cued location, and there was no need to switch attention. If we assume that the cue summoned attention to the two indicated locations, and that the attended region may also have included the location of the distractor between them (see Jans, Peters, & de Weerd, 2010; and Cave, Bush, & Taylor, 2010, for a review), then there was one neutral letter within the attentional zoom in both the 2-letter and 6-letter displays. As the items outside the attentional zoom did not receive much attention, their effect on distractor processing was minimal. In contrast, on the invalid trials, the target appeared at an uncued location. Response times were generally longer on invalid trials, perhaps partly because more time was spent with attention focused on the cued locations to determine that neither was a target. Even more time was then needed to broaden the attentional focus and/or switch attention to the other locations. This extra time allowed more opportunity for the central distractor to interfere with target processing, as can be seen in the high congruency effect in the invalid 2-letter condition. However, there was also more opportunity for dilution in the invalid 6-letter condition, as can be seen in the lower congruency effect in the invalid 6-letter condition relative to the 2-letter condition.

The results of Experiment 1 are difficult to reconcile with the perceptual load account, because the participants showed comparable degree of distractor processing in the valid and invalid 6-letter conditions, even though more letters became relevant to the search task in the invalid condition than the valid condition. Nor do the results fit with preattentive dilution or with post-selection dilution, because there is no dilution when the cues are valid. The results are consistent with zoom-limited dilution, in which items outside the cued area cannot dilute the processing of items within the cued area.

If the letters outside the attentional focus did not contribute to the degree of distractor processing in a significant way, then it is possible that dilution occurred in these experiments primarily during the initial focus of attention. The distractor compatibility effect was substantially larger in the invalid 2-letter condition than in the other 3 conditions. (See Figure 2B.) During the initial focus of attention, the distractor was the only letter in the attentional zoom in the invalid 2-letter condition, but there were other letters (i.e., the target and/or neutral letters) inside the attentional focus in the other three conditions. (See Figure 3.) Experiment 3 from Chen and Cave (2013) indicates that dilution in this type of task is only produced by letters and thus the representation of the distractor in the invalid 2-letter condition could be processed without interference, especially given that the two nontargets did not change at all with the onset of the search array. Distractor processing may also have been enhanced in this condition due to the salience of the distractor because the two nontargets within the cued region were identical to one another, making the central distractor a shape singleton within this group of three objects. This latter interpretation is consistent with previous research, which showed increased distractor processing when the salience of the distractor increased (Eltiti et al., 2005). In the present experiment, it is likely that some combination of these effects led to the substantially larger congruency effect in the valid 2-letter condition than in the other conditions.

Insert Figure 3 about here

3. Experiment 2

The goal of Experiment 2 was to verify whether the dilution effect found in Experiment 1 occurred relatively early or late in the processing stream. The timing of the dilution effect was tested by delaying the onset of the distractor, so that it was not present early on while the neutral letters within the initial attention focus were likely to be most actively processed. With the distractor absent during this time, its effect could not be diluted.

Thus, an absence of a dilution effect in Experiment 2 would support the notion that the dilution effect in Experiment 1 occurred relatively early.

3.1. Method

The method of Experiment 2 was identical to that of Experiment 1 except for the way the unneeded segments of the figure-8 stimulus for the distractor were removed. In Experiment 1, the distractor appeared at the same time as the other letters in the target display, and this was done by removing the unneeded segments of all the figure-8 stimuli simultaneously. In Experiment 2, these unneeded segments disappeared simultaneously for all the stimuli except for the distractor, which faded gradually to match the background over a period of 240 msec. By revealing the distractor gradually, we ensured that the distractor did not have an abrupt onset to capture attention. We selected 240 msec as the fade-in duration based on the result of a pilot experiment, which showed that the critical period for distractor processing occurred within 240 msec after the onset of the target array. Twenty-six new participants took part in the experiment.

3.2. Results and Discussion

Figure 4A shows the response times and Table 1 shows the error rates. Three participants' data were excluded due to high error rates (greater than 25%). A repeated-measures ANOVA showed that the participants were faster on valid (718 msec) than invalid trials (866 msec), $F(1, 22) = 39.78$, $MS_e = 25279$, $p < .001$, $\eta_p^2 = .64$, and when the display set size was 2 (732 msec) rather than 6 (852 msec), $F(1, 22) = 125.82$, $MS_e = 5261$, $p < .001$, $\eta_p^2 = .85$. They were also faster when the target and distractor were congruent (767 msec) rather than incongruent (818 msec), $F(1, 22) = 20.49$, $MS_e = 5952$, $p < .001$, $\eta_p^2 = .48$. The interaction between Validity and DisplaySize was also significant, $F(1, 22) = 17.46$, $MS_e =$

3062, $p < .001$, $\eta_p^2 = .44$, suggesting that the increase in RT from the 2-letter condition to the 6-letter condition was substantially larger on the invalid trials (154 msec) compared with the valid trials (86 msec). Finally, there was a significant interaction between Validity and Congruency, $F(1, 22) = 6.75$, $MS_e = 1834$, $p < .05$, $\eta_p^2 = .23$. (See Figure 4B.) This suggests a larger congruency effect on the invalid trials (68 msec) relative to the valid trials (35 msec). Most importantly, the 3-way interaction of Validity, DisplaySize, and Congruency was not reliable, $F(1, 22) = 1.41$, $MS_e = 1230$, $p = .25$, $\eta_p^2 = .06$.

Insert Figures 4A and 4B about here

To confirm that this pattern of data differed from that in Experiment 1, we did a combined analysis on the RT data of just the invalid trials across the two experiments. For the sake of brevity, we report only the significant interactions that involve Experiment. The only significant effect was the three-way interaction of DisplaySize, Congruency, and Experiment, $F(1, 45) = 6.21$, $MS_e = 1842$, $p < .02$, $\eta_p^2 = .12$. This result indicates that on the invalid trials the effect of neutral letters on distractor processing differed between Experiments 1 and 2. Whereas adding neutral stimuli decreased the magnitude of the congruency effect in Experiment 1, it did not influence the degree of distractor processing in Experiment 2.

For completeness, we also conducted a combined analysis on the RT data of just the valid trials across the two experiments. The only significant effect that involved Experiment was a two-way interaction between Congruency and Experiment, $F(1, 45) = 10.57$, $MS_e = 2685$, $p < .01$, $\eta_p^2 = .19$, indicating a larger congruency effect in Experiment 1 than Experiment 2. The three-way interaction of DisplaySize, Congruency, and Experiment was not significant, $F(1, 45) = 2.17$, $MS_e = 954$, $p = .15$, $\eta_p^2 = .05$. Importantly, the direction of the interaction indicates no hint of a dilution effect in the valid trials of either Experiment 1 or Experiment 2. As shown in Figures 2 and 4, there was a negligible difference in the magnitude of the congruency effect between the 2-letter and 6-letter conditions in Experiment 1, but the congruency effect was numerically larger in the 6-letter condition than in the 2-letter condition in Experiment 2.

The most important finding of Experiment 2 was the elimination of the dilution effect in the invalid condition, indicating that dilution occurred relatively early in the processing stream. The removal of line segments to create the distractor letter was delayed for 240 msec, and as a result the additional neutral letters in the 6-letter condition had no effect on the overall magnitude of the congruency effect, even though a substantial congruency effect was still found in both conditions. As the distractor was neither a new object nor an abrupt onset, the lack of a dilution effect was probably not due to the capture of attention by the distractor, which might have protected it from the effect of the neutral letters. Instead, the elimination of the dilution effect suggests that the effect of neutral stimuli on the processing of the distractor occurred during the initial focus of attention in the present paradigm. (Note that the pattern of data in Experiment 1 was also consistent with the idea that dilution occurred early in the trial.) Although there were more neutral letters inside the attentional zoom in the 6-letter condition than in the 2-letter condition upon the onset of the target display, this did not affect the processing of the distractor as it was not fully revealed yet. By the time the distractor appeared, it was likely that attention had already shifted away from its initial location. As a result, the additional neutral stimuli in the 6-letter condition did not affect the processing of the distractor. Hence, no dilution was found.

We should also consider the possibility of saccades after the search array appeared. However, because dilution arises from processing in the first 240 ms after the search array appears, it is unlikely that saccades would play much of a role in generating that dilution, because there is hardly enough time within that window for both a saccade and for the post-saccade processing that would produce the dilution. The dilution in these tasks seems to be affected by covert attention rather than by eye movements.

Together, Experiments 1 and 2 show how dilution is bounded by the allocation of attention in response to the cue. Dilution does not require that attention be distributed across a broad region. Distractor processing can be diluted by stimuli within a relatively small attended region, as long as they are actual letters. There is no dilution in the invalid 2-letter trials of Experiment 1, when attention selects two figure-8 placeholders, which illustrates that dilution is caused by interference at the level of letter identification, which is consistent with the finding of Chen and Cave (2013).

4. Experiments 3A and 3B

In Experiment 2, we showed that delaying the onset of the distractor could eliminate the dilution effect found in Experiment 1. In Experiments 3A and 3B, we investigated the role of the preknowledge of the target color (see Figure 5A). Both experiments included a location cue that is generally informative but sometimes invalid, as did the earlier experiments in this study. While the color of the target was known with certainty for trials in Experiment 3A, it was unpredictable in Experiment 3B. When the color of the target was known in advance, the participants could use this knowledge to guide attention to the target location quickly. If dilution is limited to items within the attended region, then there should be no dilution effects with either the valid or invalid location cues. In contrast, when the color of the target was unpredictable, then attention would be allocated according to the location cues rather than the target color, resulting in a dilution effect in the 6-letter condition relative to the 2-letter condition as in Experiment 1. Based on this reasoning, we predicted a dilution effect in Experiment 3B but not in Experiment 3A.

4.1. Method

The method of Experiments 3A and 3B was similar to that of Experiment 1 except for the following differences. The letters in the cue display at the beginning of the trial flashed between white and gray, just as in the previous experiments, but stimuli in the target display were all colored. They were either red (RGB = 255, 64, 64) or green (RGB = 64, 255, 64). The target had the same color as that of only one other stimulus – the one at its opposite location. The other stimuli in the display had a different color from that of the target. On valid trials, the stimuli at the two cued locations were thus a different color from those at the other locations, while on invalid trials, the cued locations shared color with two of the four uncued locations on the circle. In Experiment 3A, the participants were randomly assigned to one of two groups. For one group, the target was always red. For the other group, the target was always green. In other words, for the target-red group, the search array consisted of 2 red and 5 green stimuli. For the target-green group, the search array consisted of 2 green and 5 red stimuli. In Experiment 3B, the color of the target was unpredictable on a given trial. The target-red and target-green trials were intermixed within a block with equal frequency. Twenty-eight and thirty-four new participants took part in Experiments 3A and 3B, respectively.

Insert Figure 5 about here

4.2. Results and discussion

Figures 6A and 6B show the RTs of Experiments 3A and 3B, respectively, and Table 2 shows the error rates. A combined analysis on the RT data of the two experiments indicated that the participants were faster on valid (642 msec) than invalid trials (717 msec), $F(1, 58) = 46.49$, $MS_e = 13171$, $p < .001$, $\eta_p^2 = .44$; when the display set size was 2 (663 msec) rather than 6 (695 msec), $F(1, 58) = 54.22$, $MS_e = 2022$, $p < .001$, $\eta_p^2 = .48$; and when the target and distractor were congruent (659 msec) rather than incongruent (699 msec), $F(1, 58) = 87.71$, $MS_e = 2124$, $p < .001$, $\eta_p^2 = .60$. Validity and DisplaySize interacted, with a larger set size effect in the invalid (42 msec) than valid trials (22 msec), $F(1, 58) = 9.52$, $MS_e = 1144$, $p < .01$, $\eta_p^2 = .14$. In addition, there were several significant effects involving Experiment. Not surprisingly, there was a main effect of Experiment, $F(1, 58) = 39.40$, $MS_e = 90309$, $p < .001$, $\eta_p^2 = .40$, indicating faster responses when the color of the target was predictable (587 msec) rather than unpredictable (760 msec). Validity interacted with Experiment, $F(1, 58) = 22.44$, $MS_e = 13171$, $p < .001$, $\eta_p^2 = .28$, suggesting a larger cue effect when the color of the target was unknown (121 msec) rather than known (22 msec) on a given trial. (See Figures 8A and 8B.) When color provides very consistent information that can be used to identify the target, there seems to be less of a spatial attention effect. This suggests that knowing the target color allows participants to use it to switch attention to the target quickly on invalid trials, thereby eliminating the need to process the identity of the stimuli at the cued locations when they are in the wrong color.

Insert Figures 6A, 6B, and Table 2 about here

The effects of display set size and target-distractor congruency were also much larger when the target color was unpredictable rather than when it was predictable, $F(1, 58) = 29.45$,

MS_e = 2022, $p < .001$, $\eta_p^2 = .34$, for DisplaySize x Experiment interaction; and $F(1, 58)$ = 7.34, MS_e = 2124, $p < .01$, $\eta_p^2 = .11$, for Congruency x Experiment interaction. Most importantly, there was a significant 4-way interaction of Validity, DisplaySize, Congruency, and Experiment, $F(1, 58) = 4.64$, MS_e = 567, $p < .05$, $\eta_p^2 = .07$. The last result confirmed that the pattern of data regarding the dilution effects in the valid and invalid conditions differed in Experiment 3A from that in 3B.

Before we drew any conclusions, we first considered the possibility that the different pattern of results found in Experiments 3A and 3B was caused primarily by the different degrees of inter-trial priming between the two experiments. Previous research has shown that having the same target feature from one trial to another has a strong effect on the deployment of attention such that many effects that had previously been attributed to top-down attentional guidance could in fact be explained by inter-trial priming (Maljkovic & Nakayama, 1994; Theeuwes & van der Burg, 2011; for review, see Awh, Belopolsky, & Theeuwes, 2012; Theeuwes, 2013). To determine the degree to which our results could be accounted for by inter-trial priming, we examined separately the trials in Experiment 3B in which the color of the target was repeated for two consecutive trials (the ColorRepetition trials) and the trials in which the color of the target was switched from one trial to the next (the ColorSwitch trials). The data are shown in Tables 3A and 3B.

Insert Tables 3A and 3B about here

To compare the two types of trials, we conducted a repeated-measures ANOVA on the RTs with Color (ColorRepetition vs. ColorSwitch), Validity, DisplaySize, and Congruency as factors. Here we will focus mainly on the effects involving Color. The main effect of Color indicated faster responses when the color of the target was repeated (743 msec) rather than switched (775 msec), $F(1, 31) = 32.62$, $MS_e = 3945$, $p < .001$, $\eta_p^2 = .51$, and the Color by Validity interaction showed a larger validity effect on the ColorSwitch trials (128 msec) compared with the ColorRepetition trials (113 msec), $F(1, 31) = 4.70$, $MS_e = 1635$, $p < .05$, $\eta_p^2 = .13$. In addition, the three-way interaction of Validity, DisplaySize and Congruency was right at the boundary of significance, $F(1, 31) = 4.13$, $MS_e = 2155$, $p = .05$, $\eta_p^2 = .12$, indicating dilution. Importantly, there was no 4-way interaction among Color, Validity, DisplaySize, and Congruency, $F(1, 31) < 1$, *ns*, suggesting that the degree of dilution was comparable regardless of whether the color of the target was repeated or switched on two successive trials. These results indicate that although repeating the color of the target facilitated the overall response latencies to the target, a result consistent with prior research (e.g., Becker, 2007; Leonard & Egeth, 2008; Maljkovic & Nakayama, 1994; Theeuwes & van der Berg, 2011), it did not affect the magnitude of dilution. The smaller validity effect on the ColorRepetition trials shows faster attentional switch to the target on these trials relative to the ColorSwitch ones, presumably because the color of the target was more activated when it had been the same on a previous trial. The fact that this advantage in attentional switch did not decrease the degree of dilution in the ColorRepetition trials compared with the ColorSwitch trials suggests that the facilitation occurred relatively late, probably *after* the cued non-target stimuli were rejected as the target. This reasoning was based on the results of Experiments 1 and 2, which showed that dilution occurred relatively early in processing, before attention has shifted in the invalid trials. Thus, whereas inter-trial priming facilitated the allocation of attention to the cued location and the switching of attention to the target after the initial cued stimuli were processed and rejected, it did not affect the degree of processing of the cued stimuli during the initial focus of attention.

A similar analysis was conducted on the error rates. The only significant result involving Color was a 4-way interaction of Color, Validity, DisplaySize, and Congruency,

$F(1, 31) = 6.37$, $MS_e = 12$, $p < .05$, $\eta_p^2 = .17$. To clarify the interaction, two analyses were conducted, one on the ColorRepetition trials, and the other on the ColorSwitch trials. For the ColorRepetition trials, in addition to the main effects of DisplaySize, $F(1, 31) = 6.75$, $MS_e = 14$, $p < .05$, $\eta_p^2 = .18$, and Congruency, $F(1, 31) = 5.72$, $MS_e = 35$, $p < .05$, $\eta_p^2 = .16$, there was a significant 3-way interaction of Validity, DisplaySize and Congruency, $F(1, 31) = 4.63$, $MS_e = 16$, $p < .05$, $\eta_p^2 = .13$. The 3-way interaction indicated an increase in the congruency effect from the 2-letter to 6-letter displays on the valid trials, but a decrease (i.e., dilution) from the 2-letter to 6-letter trials on invalid trials. For the ColorSwitch trials, the only significant result was the main effect of congruency, $F(1, 31) = 6.56$, $MS_e = 51$, $p < .05$, $\eta_p^2 = .17$. The 3-way interaction of was not significant, $F(1, 31) = 1.66$, $MS_e = 10$, $p = .21$, $\eta_p^2 = .05$. Thus, although the RTs indicate that dilution appeared regardless of color repetition, that dilution only becomes apparent in the error rates when the target color is repeated from the previous trial.

Taken together, these results show that the differential degree of dilution found in Experiments 3A and 3B were unlikely to be caused by inter-trial priming. If anything, evidence for dilution on the invalid trials in Experiment 3B was slightly stronger when the color of the target was repeated from one trial to another compared with when the color of the target switched between trials, suggesting that inter-trial priming did not contribute to the lack of dilution effect found in Experiment 3A. Consistent with previous research, which found evidence for attentional guidance by top-down knowledge despite the target being a salient stimulus such as a shape or color singleton (e.g., Lamy, Carmel, Egeth, & Leber, 2006; Leonard & Egeth, 2008), Experiment 3A showed that knowing the color of the target influenced attentional guidance and eliminated the dilution effect on the invalid trials. Even though the participants still needed to shift attention when the cue was invalid, they were able to use their preknowledge of the target color to guide attention to the target quickly, allowing them to reject the stimuli that had the wrong color without much processing. This would allow the participants to narrow their attentional zoom quickly to only those stimuli that possessed the target color. As the neutral letters with a task-irrelevant color were excluded from the attentional zoom without being fully identified, they had little effect on the processing of the distractor. No dilution was found in either the valid or invalid trials when the color of the target was predictable in Experiment 3A, as predicted by the zoom-limited dilution account. In contrast, when the color of the target was unpredictable in Experiment 3B, locating the target would take longer when the cue was invalid. As the irrelevant-colored neutral stimuli at the cued locations could not be rejected based on a quick assessment of their color, they would have more opportunity to receive attention, resulting in decreased distractor processing in the 6-letter condition compared with the 2-letter condition.

The finding of a dilution effect in Experiment 3B but not in Experiment 3A is also consistent with the result of a previous study (Experiment 4 in Chen & Cave, 2013), in which the participants showed a dilution effect only when they had no preknowledge of the target color on a given trial. In that experiment, the target was preceded by a non-informative precue that cued all the 6 possible target locations in a search array in both a 2-letter condition and a 6-letter condition. The color of the target was predictable for half of the participants, and unpredictable for the other half. A dilution effect was found only in the latter group. Thus, in that experiment and in Experiments 3A and 3B of the present study, dilution effects were abolished by top-down color selection, which helped to guide attention to the target efficiently. In addition to demonstrating how dilution is limited by attentional selection, this new result also demonstrates just how effectively color information can be used to guide attention, because it was done by participants in Experiment 3A even though they also had informative location cues to guide attention. The lack of dilution in Experiment

3A demonstrates that when attention is directed by a known target color, it can quickly and effectively block the processing of stimuli with the wrong color.

5. Experiments 4A and 4B

While Experiments 3A and 3B tested how dilution is affected by attention that is directed by a known target color, Experiments 4A and 4B will test the influence of color grouping that is independent of expectations about target features. In Experiments 3A and 3B, the majority of the neutral stimuli grouped with the distractor, and a dilution effect was found when the target appeared at an uncued location and its color was unknown in advance. In the next two experiments, we explored the effect of perceptual grouping by color. We made the distractor a color singleton so that the neutral stimuli grouped with the target instead of with the distractor. In Experiment 4A, the distractor had a task-relevant color: it was either red or green (see Figure 5B). In Experiment 4B, it had a task-irrelevant color, which was yellow (see Figure 5C). As the neutral stimuli now differed from the distractor in location, shape, and color, we expected their effect on the distractor to be reduced, and this in turn should reduce or eliminate the dilution effect found in Experiment 3B. Furthermore, any diminution in the dilution effect in either Experiment 4A or 4B will be attributable primarily to bottom-up factors, for the color of the distractor in Experiment 4B is task-irrelevant. We will discuss this last point in more detail in the discussion section below.

5.1. Method

The method was the same as that of Experiment 3B except that the distractor was a color singleton. In other words, in Experiment 4A, the distractor was equally likely to be red among green stimuli or green among red stimuli. In Experiment 4B, it was yellow (RGB = 255, 255, 0) among green stimuli on half the trials and yellow among red stimuli on the rest of the trials. As in Experiment 3B, the color of the target was unpredictable on a given trial. Forty-seven new participants (32 in Experiment 4A and 15 in Experiment 4B) took part in the study.

5.2. Results and Discussion

Figures 7A and 7B show the response times of Experiments 4A and 4B, respectively, and Table 4 shows the error rates. The data from three participants, 2 from Experiment 4A and 1 from Experiment 4B, were excluded due to long RTs (over 3 standard deviations above the average RT of the rest of the participants in their respective group) and/or high error rates (over 40% in multiple conditions). A mixed ANOVA on the RT data showed that the participants were faster on the valid (773 msec) than invalid trials (886 msec), $F(1, 42) = 65.08$, $MS_e = 15884$, $p < .001$, $\eta_p^2 = .61$, in the congruent (795 msec) than incongruent (865 msec) condition, $F(1, 42) = 61.24$, $MS_e = 5686$, $p < .001$, $\eta_p^2 = .59$. and on the 2-letter (796 msec) than the 6-letter (863 msec) trials, $F(1, 42) = 105.96$, $MS_e = 3671$, $p < .001$, $\eta_p^2 = .72$. Furthermore, Validity interacted with DisplaySize, $F(1, 42) = 4.41$, $MS_e = 1269$, $p < .05$, $\eta_p^2 = .10$, indicating a larger set size effect in the invalid (74 msec) than valid trials (60 msec) trials. There were no significant results involving Experiment, and no other effects were significant. The analyses on the accuracy data showed 3 significant results. In addition to the main effects of Validity, $F(1, 42) = 10.37$, $MS_e = 11$, $p < .01$, $\eta_p^2 = .20$, and Congruency, $F(1, 42) = 20.20$, $MS_e = 32$, $p < .001$, $\eta_p^2 = .32$, there was a significant main effect of Experiment, $F(1, 42) = 4.34$, $MS_e = 83$, $p < .05$, $\eta_p^2 = .09$. The last result indicates that the participants in Experiment 4A made more errors (5.6% error rates) than the participants in Experiment 4B (3.4% error rates).

Insert Figures 7A, 7B, Table 4, and Figure 8 about here

Experiments 3B, 4A and 4B are generally matched in the layout of the stimuli, the need for letter identification, and the lack of foreknowledge about the stimulus color. They differ only in the arrangement of the two colors, and this difference was enough to prevent dilution in Experiments 4A and 4B. (See Figures 8C and 8D.) There are two factors that could be preventing dilution in these experiments. The first is grouping by color: when neutral stimuli at the cued locations had the same color as the distractor in the invalid trials of Experiment 3B, spatial segregation between them could not completely prevent the distractor from being influenced by the neutral stimuli. However, when the neutral stimuli differed from the distractor in both location and color in Experiments 4A and 4B, they no longer affected the processing of the distractor. Segregation by color in addition to location may have helped to protect the representation of the distractor from interference. Color grouping effects on dilution have also been demonstrated by Yeh and Lin (2013). They emphasized that dilution was strong when the diluting nontargets were grouped by color with the target, but the current results show that even with this target-nontarget grouping, a salient distractor can overcome dilution. This new result demonstrates that in addition to the target-nontarget grouping, other factors, such as the grouping between the distractor and the diluting nontargets, and the location of the distractor, must also be considered.

The second factor that may help to explain why the distractor interference was able to overcome dilution in Experiments 4A and 4B is that the distractor may have received additional attention because it was a color singleton in these displays, and if so, this extra attention may have allowed the distractor to overcome the dilution from the other items in the display. In some conditions of Yeh and Lin's (2013) experiments, the distractor was also a color singleton, but it did not produce a congruency effect. In their stimulus arrangement, however, the singleton distractor was at the periphery, not near any items of the other color, and it had the same color for all trials within a block. Meanwhile, the target, whose color also stayed the same throughout a block, was always at a central location. These stimulus features may have made Yeh and Lin's singleton distractor less capable of drawing attention, as shown by Belopolsky and colleagues (Belopolsky & Theeuwes, 2010; Belopolsky, Zwaan, Theeuwes, & Kramer, 2007), who found that singletons captured attention when they were inside but not outside the attentional zoom.

One might argue that because the color of the distractor in Experiment 4A was also the color of the target on other trials, it is possible that part or all of the effect found in that experiment was due to top-down processes instead of bottom-up factors. Perhaps the distractor received extra attention because it had a task-relevant color that the participants held in memory, for they knew that the target might appear in that color. As the contents of working memory are known to facilitate the deployment of visual attention to those stimuli in some visual search tasks (Chen & Tsou, 2011; Downing, 2000; Olivers, Meijer, & Theeuwes, 2006), holding the task-relevant color in mind could result in increased attention to the distractor, which in turn could lead to the elimination of the dilution effect in Experiment 4A.

In light of the results of Experiment 4B, it is unlikely that top-down processes played a significant role in the results of Experiment 4A. In Experiment 4B, the distractor had a task-irrelevant color. The participants would have no incentive to hold the color in mind, and yet no dilution effect was found. These results showed that although a distractor with a task relevant color impaired performance more than a distractor with a task irrelevant color, having a task-relevant color appeared to incur a general cost rather than affecting the degree of distractor processing in a specific way. The absence of a dilution effect in both

Experiments 4A and 4B seems most likely due to the bottom-up factors driven by color boundaries that we discussed above.

Because the color boundaries are unrelated to the relevance of the stimuli to the task, an explanation for the effects of these color boundaries does not arise out of perceptual load theory. Likewise, neither preattentive dilution nor post-selection dilution offer an explanation of these effects of singleton color. However, once we accept the claim underlying zoom-limited dilution that the interference underlying dilution occurs only within attentional boundaries, then it becomes easier to understand how attention allocated to a color singleton could insulate it from dilution.

6. General Discussion

These experiments explore the complex interactions among target and distractor stimuli when attention is directed (and sometimes misdirected) to specific locations in the stimulus array. The congruency effect from the central distractor allows the zoom-limited dilution account to be compared against accounts based on preattentive dilution, post-selection dilution, and perceptual load. The results provide new evidence that the interference that causes dilution only arises from stimuli within the attended region. Because dilution is linked to the allocation of attention, dilution can be used to determine the degree to which nontarget letters in the display are attended.

Experiments 1 and 2 show that spatial cues allow attention to be effectively constricted, so that the uncued locations on the ring are excluded. When nontargets appear at those uncued locations, they do not affect processing of the central distractor. However, there can still be dilution with this narrow attentional zoom, because stimuli appearing at the cued locations have a very noticeable effect. When the cued locations contain letters (either targets or nontargets), these letters limit the processing of the central distractor (dilution). When the cued locations contain nonletter placeholders (the invalid 2-letter condition), the central distractor is processed without dilution, producing a larger congruency effect. Experiment 2 shows that much of the congruency effect from the central distractor and all of the dilution from the cued letters occur relatively early in the trial, before attention might have shifted in the invalid trials. In the later part of the invalid trials, when the distractor is fully revealed, attention has presumably been shifted primarily to the target, preventing the nontargets from generating dilution at that time. Overall, it is the nontarget letters appearing at the cued locations that are responsible for most of the dilution, and not those appearing at uncued locations.

Thus, the dilution measure indicates that in this paradigm, attention starts at the cued locations at the beginning of the trial, and stays there long enough to determine whether either letter there is a target. If both are found to be nontargets, attention then shifts to the target location.

Experiments 3 and 4 show that dilution is also limited by attention that is driven by top-down or bottom-up color information, and they also provide a further illustration of how dilution can be used to get a fuller picture of attentional control in complex displays. In Experiment 3A, the participants' foreknowledge about the upcoming target's color is more accurate than their foreknowledge of its location. As soon as the cued items are determined to be the wrong color, attention is shifted to the letters with the right color. The shift occurs quickly, before the letters at the cued locations are identified, and their effect on the central distractor is thus limited, as can be seen from the absence of dilution by the nontargets.

When the ability to predict the target color is removed (Experiment 3B), participants must analyze the shapes at the cued locations to identify them. Only after they are both eliminated as targets is attention directed elsewhere, which takes longer and allows both the central distractor and the neutral nontarget letters to exert stronger effects. Interestingly, participants in this experiment do know that the target will be in the smaller color group, even though they do not know which color that smaller group will have. We might expect that they would use the bottom-up color difference to direct attention to the smaller group, but they do not appear to be able to use this strategy effectively to guide attention. However, it would be wrong to conclude that bottom-up color differences are unable to direct attention in these tasks, because Experiments 4A and 4B show that the central distractor is insulated from dilution by the neutral nontarget letters when they are different colors. Thus, bottom-up color differences do shape the allocation of attention in this task, but they are not used as effectively as they might be.

These experiments were designed to explore the dilution effects of irrelevant stimuli in a complex visual array. Dilution became the focus of much research after Tsal and Benoni (2010; Benoni & Tsal, 2010) and Wilson et al. (2011) proposed it as an alternative to perceptual load theory (Lavie, 2005; Lavie & Tsal, 1994), which postulates that attention is first allocated to stimuli relevant to the current task, and that any remaining attentional resources are allocated to irrelevant stimuli. However, neither the preattentive form of dilution (suggested by Tsal and Benoni) nor the post-selection form of dilution (advocated by Wilson et al.) predict that dilution will be shaped by spatial cues, top-down expectations of target color, or bottom-up color boundaries as shown in these experiments. These results suggest that dilution occurs between objects within the area selected by the attentional zoom.

A dilution account that links interference to attentional zoom shares some properties with perceptual load theory. If an experimental manipulation is designed to increase perceptual load, it may have the effect of narrowing the attentional zoom to select a smaller region, and if it does, it will limit or eliminate interference from items outside the attentional zoom, producing results similar to those predicted by perceptual load theory. However, perceptual load theory is inconsistent with the singleton effects in Experiments 4A and 4B, and is also inconsistent with the equivalent performance across the valid and invalid 6-letter conditions of Experiment 1, while these results fit within a zoom-limited dilution account. As mentioned in the introduction, there are a large number of other experimental results that challenge perceptual load theory as well. Thus, in many visual tasks, competition within the attentional system will lower attention to nontargets when the processing needs of the targets go up, in line with the general principles motivating perceptual load theory. However, there are other factors involved, such as attentional zoom settings, that are not considered in perceptual load theory or in either form of the dilution account. Thus, making specific experimental predictions about how processing demands affect attention to nontargets will probably require more specific models of how stimuli are prioritized and how attentional processing resources are allocated, as suggested by Kyllingsbaek, Sy, and Giesbrecht (2011).

Because dilution is linked to attention, measures of dilution provide a new way of monitoring the control of attention in the processing of complex stimulus arrays. In this case, the rise and fall of the dilution effects show just how effective spatial and color cues are in excluding attention from uncued locations, and how effective they are at enhancing the processing of cued stimuli, even when they are often nontargets. Color differences between stimuli also influence attentional allocation, with dilution prevented when the distractor is a color singleton that is segregated by color from the diluting nontargets, reflecting the effects of color grouping and/or attentional capture.

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Note:

1. In all the experiments reported in this paper, response latencies greater than 2000 msec were excluded. These constituted less than 2% of the total data in each experiment. Only trials with correct responses were included in the RT results in the tables, figures, and statistical analyses.

Acknowledgments

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Figure Captions

Figure 1. Examples of valid and invalid trials from Experiment 1. The target was either an H or an S. On valid trials, which comprised 60% of the trials, the target would appear at one of the two cued locations. On invalid trials, which comprised 40% of the trials, the target would occur at one of the uncued locations with equal frequency. Regardless of the cue validity, the target display was equally likely to consist of 2 letters or 6 letters, excluding the critical distractor, which was always at the center of the display. Note that the stimuli were white or gray presented against a black background, and the cue was signalled by offset transients.

Figure 2. Mean reaction times and congruency effects (incongruent RT – congruent RT) across the different conditions of Experiment 1. Error bars show the standard error of the mean.

Figure 3. Schematic representations of the locations of the initial attentional zoom upon the onset of the target in different experimental conditions. Note that the ovals formed by the dotted lines were not present in the actual experiment.

Figure 4. Mean reaction times and congruency effects (incongruent RT – congruent RT) across the different conditions of Experiment 2. Error bars show the standard error of the mean.

Figure 5. Examples of 2-letter and 6-letter trials in Experiments 3A and 3B (A), Experiment 4A (B), and Experiment 4B (C).

Figure 6. Mean reaction times across the different conditions of Experiments 3A and 3B. Error bars show the standard error of the mean.

Figure 7. Mean reaction times across the different conditions of Experiments 4A and 4B. Error bars show the standard error of the mean.

Figure 8. Congruency effects in Experiments 3A (A), 3B (B), 4A (C), and 4B (D). Error bars show the standard error of the mean.

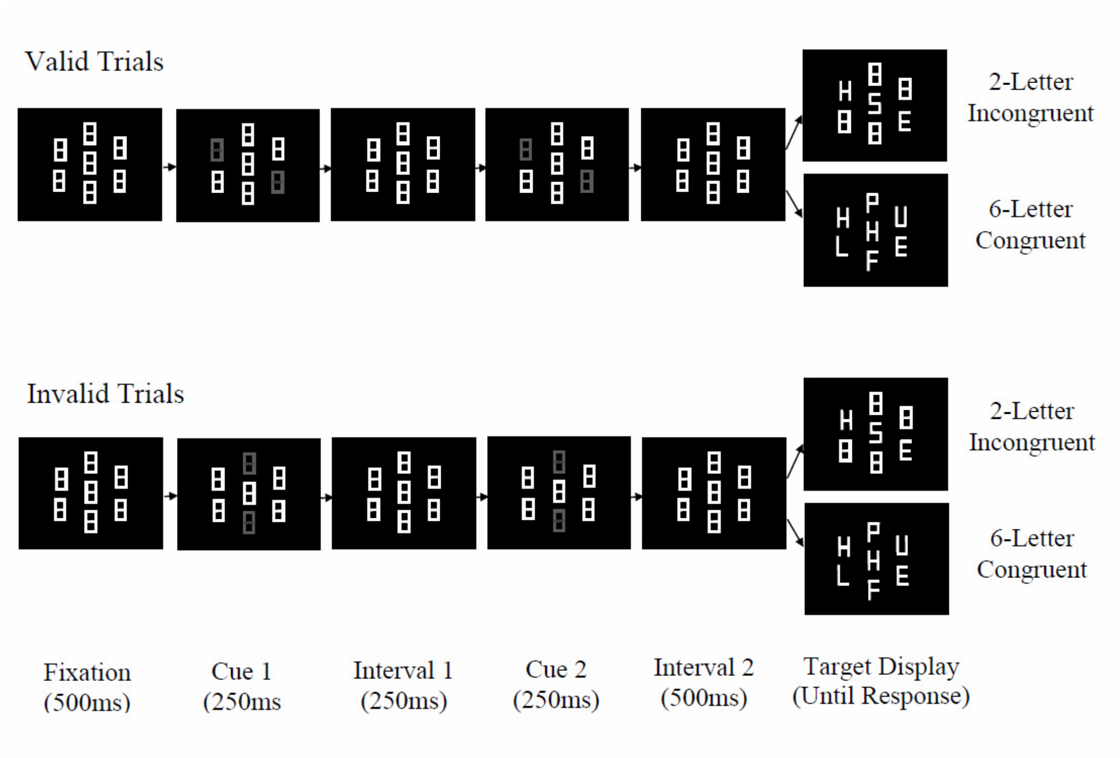

Valid Trials
2-Letter
Incongruent
6-Letter
Congruent
Invalid Trials
2-Letter
Incongruent
6-Letter
Congruent
Fixation
(500ms)
Cue 1
(250ms
Interval 1
(250ms)
Cue 2
(250ms)
Interval 2
(500ms)
Target Display
(Until Response)

Figure 2A

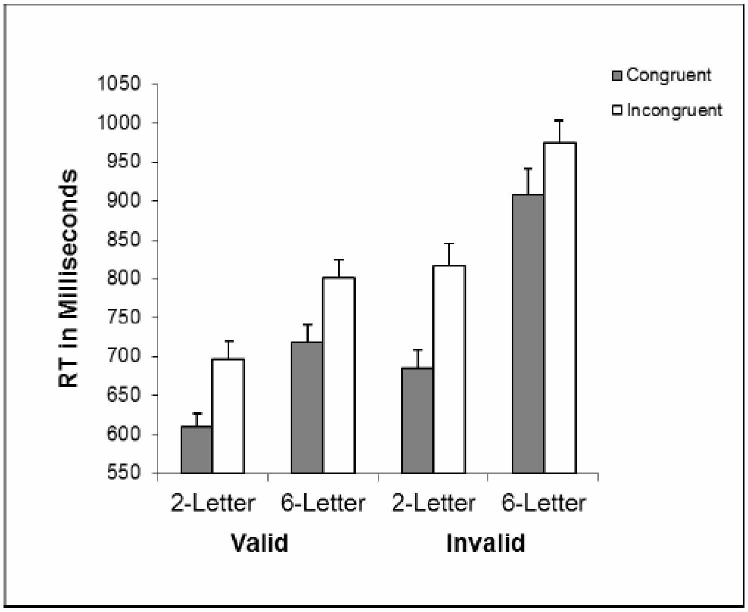
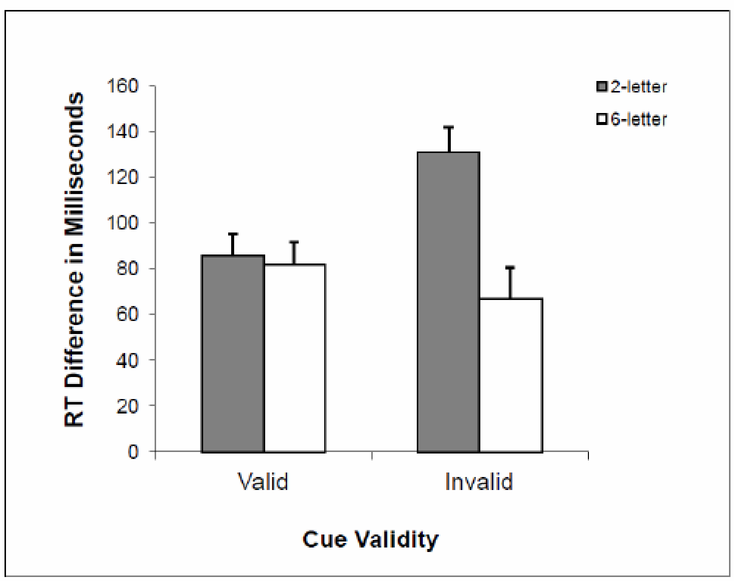


Figure 2B



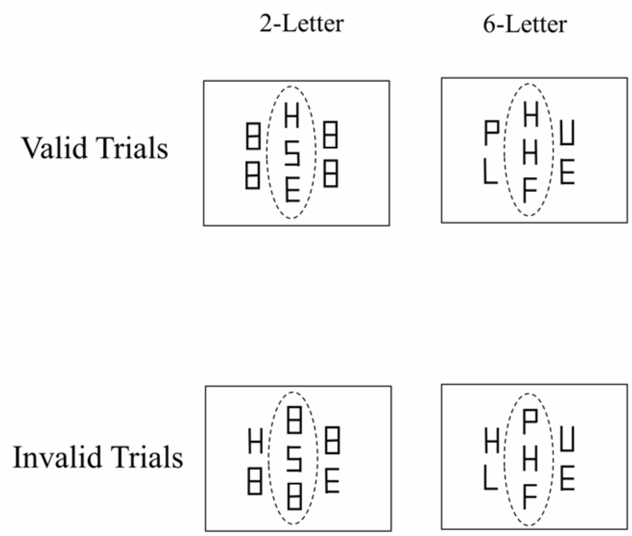

2-Letter
6-Letter
Valid Trials
Invalid Trials

Figure 4A

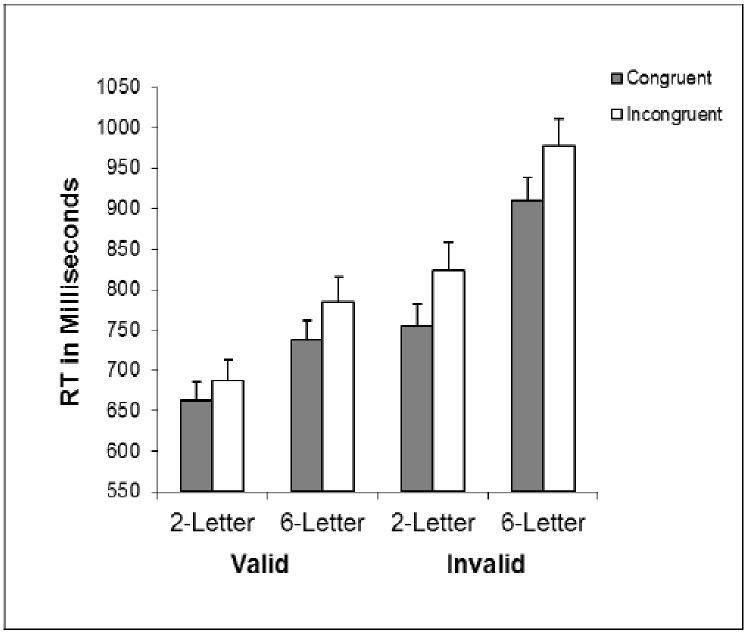
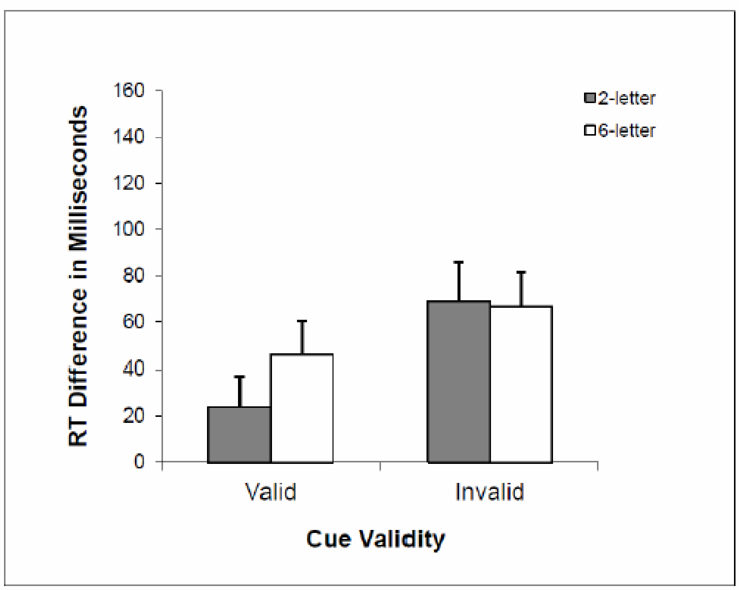


Figure 4B

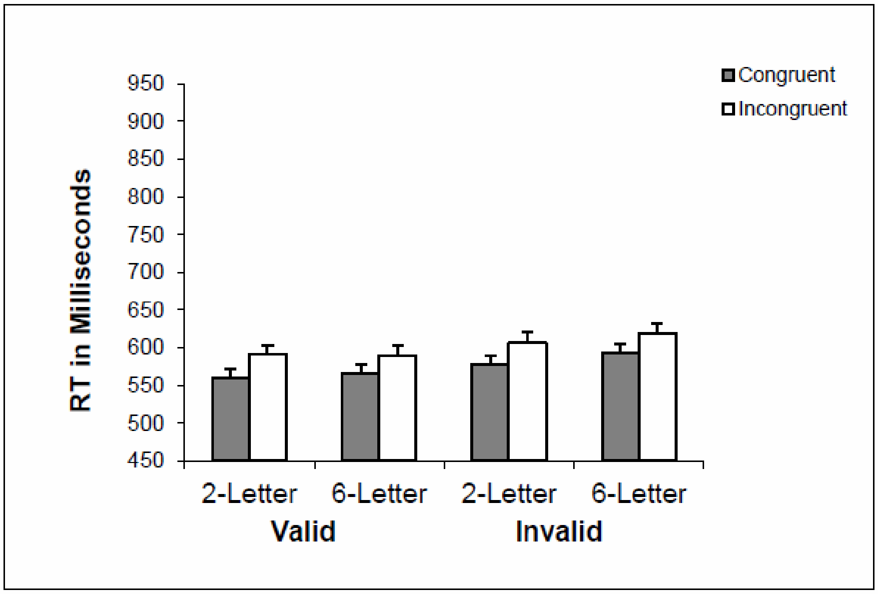


A. Stimuli from Experiments 3A and 3B

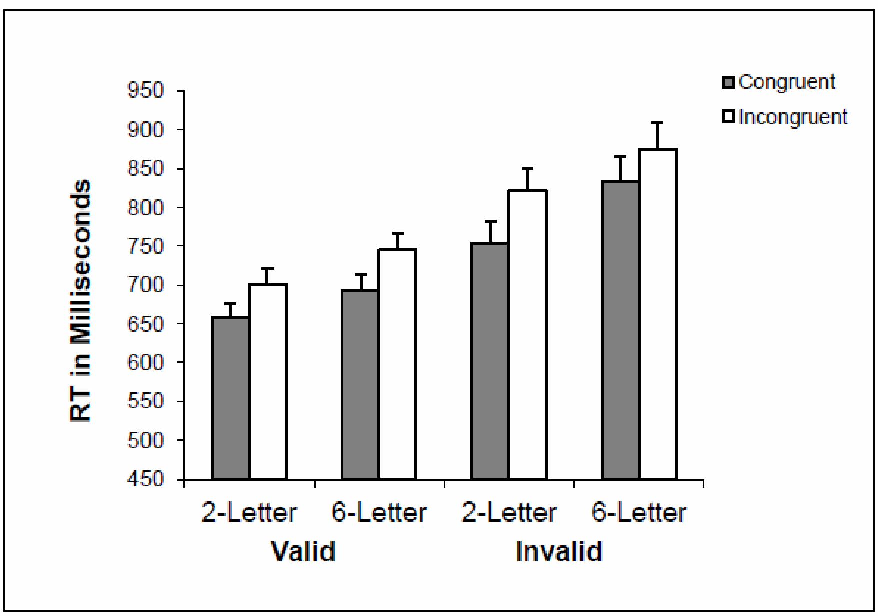
B. Stimuli from Experiment 4A

C. Stimuli from Experiment 4B

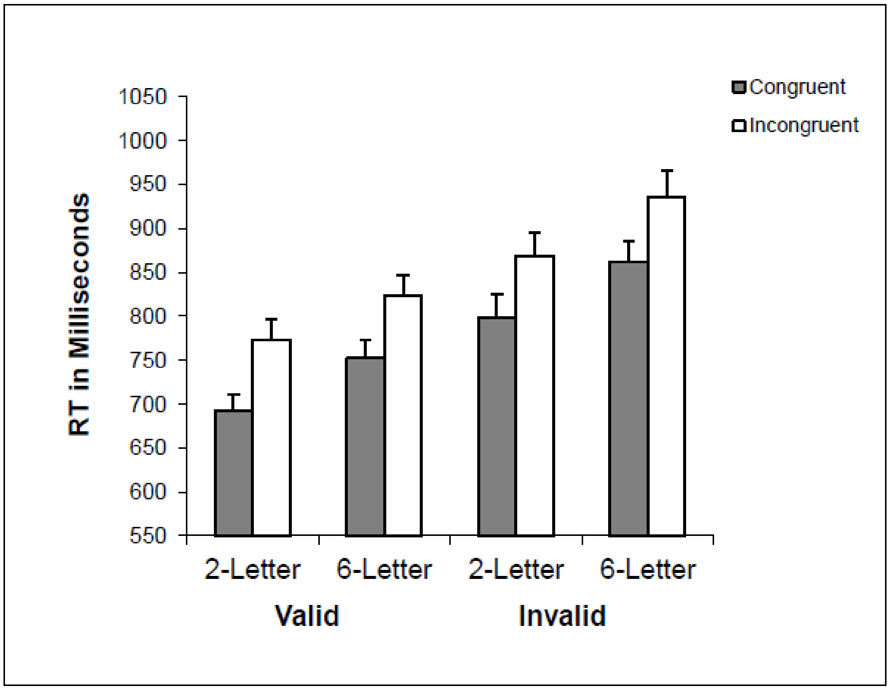
A


Congruent
Incongruent
RT in Milliseconds
950
900
850
800
750
700
650
600
550
500
450
2-Letter
6-Letter
2-Letter
6-Letter
Valid
Invalid

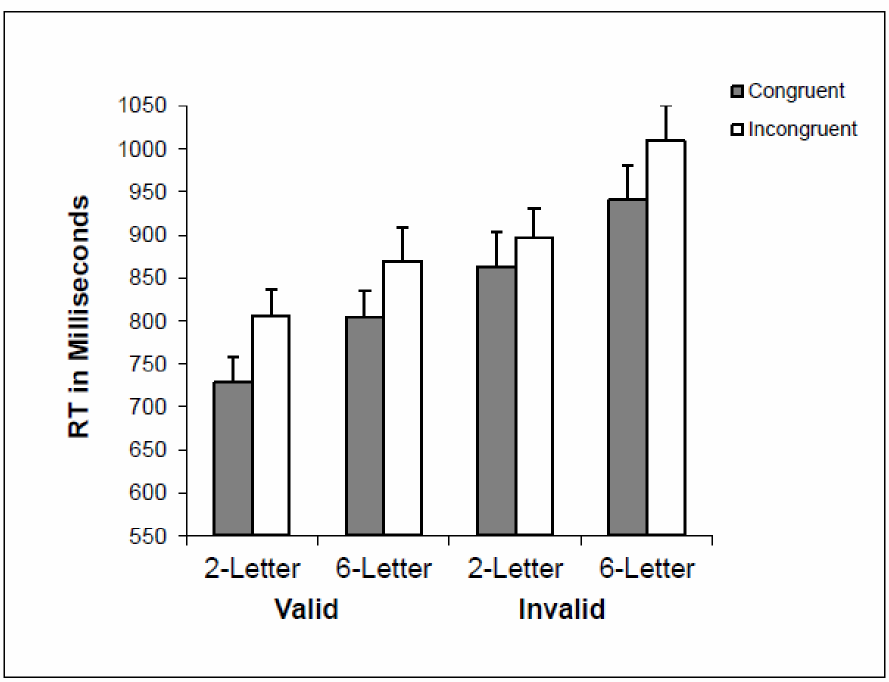
B


Congruent
Incongruent
RT in Milliseconds
950
900
850
800
750
700
650
600
550
500
450
2-Letter
6-Letter
2-Letter
6-Letter
Valid
Invalid

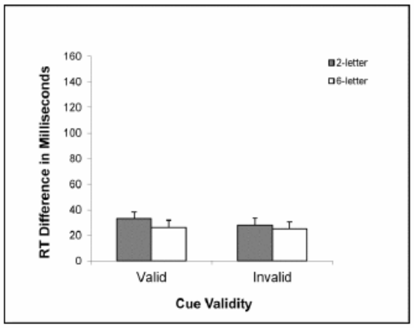
A


Congruent
Incongruent
1050
1000
950
900
850
800
750
700
650
600
550
RT in Milliseconds
2-Letter
6-Letter
2-Letter
6-Letter
Valid
Invalid

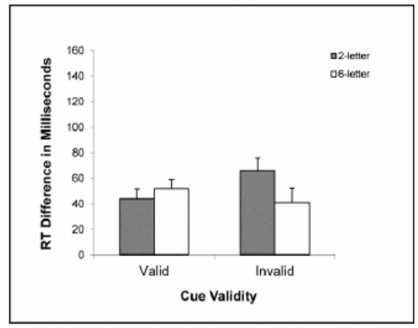
B


Congruent
Incongruent
1050
1000
950
900
850
800
750
700
650
600
550
RT in Milliseconds
2-Letter
6-Letter
2-Letter
6-Letter
Valid
Invalid

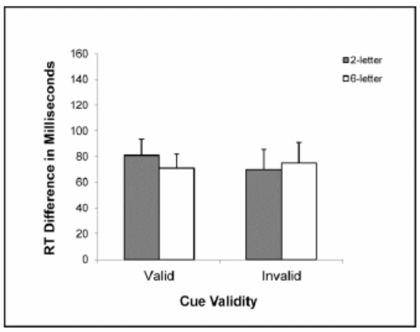
A. Experiment 3A Congruency Effects



B. Experiment 3B Congruency Effects



C. Experiment 4A Congruency Effects



D. Experiment 4B Congruency Effects

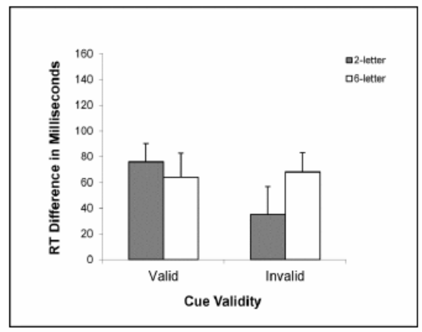


Table 1

Error rates as a function of cue validity, display set size, and target-distractor congruency in Experiments 1 and 2.

	Cue Validity			
	Valid		Invalid	
Display Set Size	C	I	C	I
	Experiment 1			
2-letter	3.7 (0.7)	5.7 (0.9)	3.7 (0.7)	7.1 (1.4)
6-letter	3.7 (0.7)	4.9 (0.9)	3.9 (0.7)	5.5 (1.2)
	Experiment 2			
2-letter	4.1 (0.7)	5.4 (0.8)	3.7 (0.7)	7.2 (1.0)
6-letter	4.4 (1.1)	5.5 (0.8)	4.2 (0.8)	6.9 (1.2)

C, Congruent; I, Incongruent. Standard errors are in the parentheses.

Table 2

Error rates as a function of cue validity, display set size, and target-distractor congruency in Experiments 3A and 3B.

	Cue Validity			
	Valid		Invalid	
Display Set Size	C	I	C	I
	Experiment 3A			
2-letter	3.4 (0.4)	3.8 (0.5)	2.2 (0.4)	3.6 (0.6)
6-letter	2.6 (0.4)	3.6 (0.6)	2.8 (0.5)	4.3 (0.6)
	Experiment 3B			
2-letter	4.1 (0.6)	4.9 (0.8)	2.6 (0.6)	5.5 (1.2)
6-letter	3.3 (0.5)	5.3 (0.8)	3.6 (0.6)	6.2 (1.2)

C, Congruent; I, Incongruent. Standard errors are in the parentheses.

Table 3A

Mean reaction times and error rates as a function of cue validity, display set size, and target-distractor congruency for the ColorRepetition trials in Experiment 3B.

	Cue validity			
	Valid		Invalid	
Display set size	C	I	C	I
	Reaction times (ms)			
2-letter	649 (18)	688 (19)	738 (28)	803 (29)
6-letter	672 (20)	737 (21)	806 (33)	852 (36)
	Error rates (% incorrect)			
2-letter	3.9 (0.8)	4.1 (0.8)	1.4 (0.6)	5.1 (1.3)
6-letter	3.5 (0.6)	5.5 (1.1)	4.5 (0.9)	5.8 (1.4)

Note: C = Congruent, I= Incongruent. Standard errors are in the parentheses.

Table 3B

Mean reaction times and error rates as a function of cue validity, display set size, and target-distractor congruency for the ColorSwitch trials in Experiment 3B.

	Cue validity			
	Valid		Invalid	
Display set size	C	I	C	I
	Reaction times (ms)			
2-letter	666 (19)	714 (20)	769 (30)	836 (29)
6-letter	712 (22)	751 (21)	858 (34)	894 (36)
	Error rates (% incorrect)			
2-letter	4.3 (0.6)	5.7 (1.0)	3.7 (0.9)	5.6 (1.3)
6-letter	3.5 (0.7)	5.1 (0.9)	2.7 (0.6)	6.9 (1.3)

Note: C = Congruent, I= Incongruent. Standard errors are in the parentheses.

Table 4

Error rates as a function of cue validity, display set size, and target-distractor congruency in Experiments 4A and 4B.

	Cue Validity			
	Valid		Invalid	
Display Set Size	C	I	C	I
	Experiment 4A			
2-letter	3.1 (0.5)	5.7 (0.9)	4.3 (0.9)	8.2 (1.1)
6-letter	3.5 (0.5)	6.2 (0.9)	4.1 (0.5)	9.6 (1.6)
	Experiment 4B			
2-letter	2.3 (0.6)	4.2 (0.9)	2.4 (0.6)	4.5 (1.2)
6-letter	1.6 (0.5)	4.6 (1.1)	3.1 (0.7)	4.6 (1.2)

C, Congruent; I, Incongruent. Standard errors are in the parentheses.

Highlights

Attentional zoom limits how distractor processing is diluted by other display items.
Dilution occurs mainly within attentional boundaries before attention is switched.
Foreknowledge of target color can override the cuing effect and eliminate dilution.
Dilution is also eliminated when the distractor is a color singleton.
Dilution shows how effectively spatial and color cues are used to direct selection.